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Volume 38 July, 1952 *Number 7*

Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

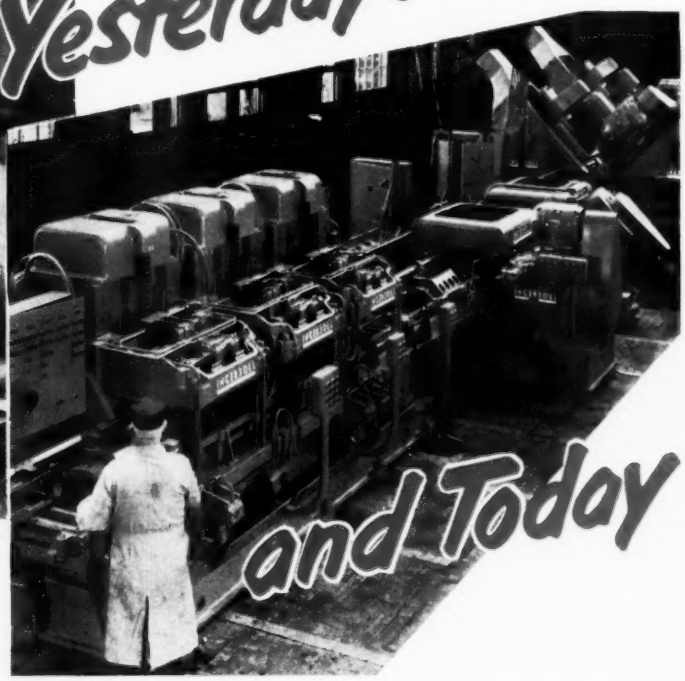
THIS ISSUE

SOME RECENT CONCEPTS OF MACHINABILITY

PUBLISHED BY
THE TEXAS COMPANY
TEXACO PETROLEUM PRODUCTS

MACHINING

Yesterday...



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Fifty years ago, you couldn't have used one of today's fabulous multi-automatics even if you'd had it. With the cutting fluids then available your work would probably have stalled before you got it beyond the first station.

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To keep Texaco in the van of the metal working field, laboratory research men and practical cutting oil engineers work hand in hand. This union of the practical with the theoretical is a major reason why it can be said: *"Whatever the metal or your method of working it, you can machine it better, faster and at lower cost with Texaco."*

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LUBRICATION

A TECHNICAL PUBLICATION DEVOTED TO THE SELECTION AND USE OF LUBRICANTS

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Vol. XXXVIII July, 1952 No. 7

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Some Recent Concepts of Machinability

More and more metal products of longer life and greater precision to satisfy the demands for both our normal living needs and our military requirements — such is the pattern of industry today. Bridging the gap between the raw material and the finished product stand the various metal processing operations, of which metal cutting and machining are perhaps the most important. Unheralded and unpublicized, the machining of metals, nevertheless, might well be considered the most critical and essential link in the chain of operations from the mine to the factory.

Cutting and machining of metals is, at best, a most complex operation. The problems induced by increased production, coupled with those arising from the introduction of new metals and alloys which have not heretofore been machined, present the metal working industry with the greatest challenge in its history. From the practical angle of economics and efficiency, increased production means higher cutting speeds and longer cutting tool life. In addition, the new non-ferrous alloys of improved physical properties and resistance to corrosion and high temperatures are much more difficult to machine than the conventional alloys and require entirely different machining techniques.

Development in all basic industrial fields passes through three phases. The first is empirical during which progress and advancement rely primarily upon the extent of the "know how" that has been accumulated over a period of time. The second begins when science and technology apply their experience and methods toward establishing the fundamental principles and laws that govern the particular process or operation involved. From a practical standpoint, theories and scientific principles are of interest to the man in the shop only insofar as they can be used to assist him in improving his operations. Often, in the beginning, phases one and two seem to be at odds with one another, but as time goes on, it is inevitable that the gap close and eventually the two must merge into one. The third phase begins when the differences between the "know how" and the "know why" are sufficiently reconciled that the two can join forces and work together for the advancement of the particular field involved.

Metal cutting has long been an art but has only recently entered into the second phase of its development. In order to keep abreast of needs and requirements, it is essential that the fundamental principles of machining be clearly understood. It is quite apparent that there are many variables involved in the actual cutting processes. Some of them have been identified and their effects and inter-relationships established. Others have been recognized but have not yet been investigated to the extent that rules governing their behavior can be formulated. Undoubtedly there are still others which so far have escaped detection. Current research and development work is directed toward establishing all of the basic principles involved in machining. Technical information is now being

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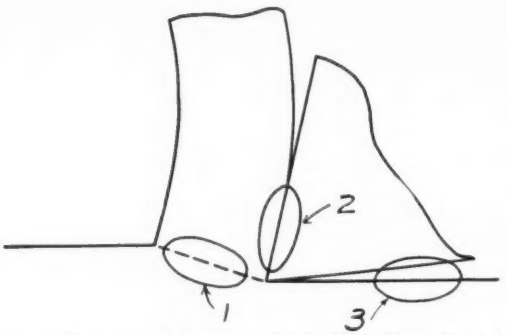


From Metal Cutting Principles, 1952 by M. C. Shaw of M.I.T.

Figure 1 — Areas of interest in machining. See discussion pages 82 and 83 below.

accumulated at a rapid rate, and although differences still exist in correlation of this information with experience, nevertheless today the industry stands on the threshold of almost complete transition from an art to a science. The fundamentals and principles of some of the phases of metal cutting, as they appear in the current literature, are discussed in the following pages. It is realized that some of the concepts included herein may still be of a controversial nature, but they are presented solely on the basis that a review of the available material indicates them to be representative of the present thinking and *no attempt is made to discuss the pros and cons of any of the phases.*

The word machinability itself, although one of the most widely used words throughout the metal cutting industry, defies a strict definition, as it has different meanings to different people at different times. To most tool engineers, machinability connotes a combination of characteristics of a cutting operation, including (1) the life of the cutting tool, (2) the surface quality of the finished work, and (3) the power consumed in machining a metal. The relative importance of these three factors depends on the nature of the operation, the equipment being used, and the ultimate use of the finished product.

Mechanics of Metal Cutting

One of the first things which must be clarified and firmly established is the mechanism involved when metal is machined. As might be suspected, numerous theories have been proposed over the years to explain the phenomena that occur when metal is cut. However, the early investigators were seriously handicapped by the lack of proper techniques and instrumentation, and consequently their theories lacked experimental verification, thus leading to the existence of many false concepts, some of which still remain.

Through the use of devices currently available to the scientist, including modern photographic and metallographic procedures, a wealth of information has been accumulated by numerous investigators working independently from which it has been possible to establish basic mechanics of metal cutting currently accepted.

TWO FUNDAMENTAL PROCESSES INVOLVED IN CHIP FORMATION

There seem to be two fundamental physical processes involved in all metal cutting operations, namely:

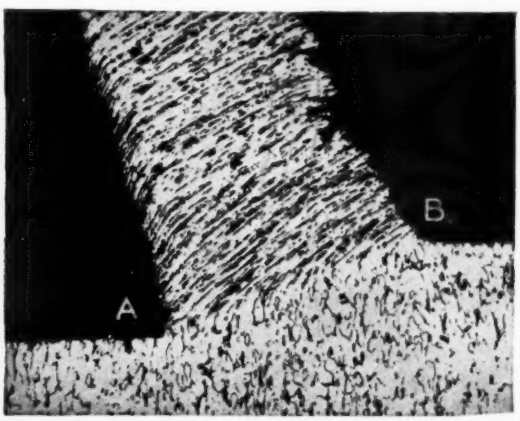
(1) A shearing process whereby the chip is formed.

(2) Movement of the chip up the face of the tool.

A schematic diagram of the chip formation showing the three areas of significance is presented in Fig. 1. As the cutting tool advances through the workpiece, the metal, instead of being fractured on a line parallel to its surface, is actually sheared in a narrow zone starting at the cutting edge of the tool and proceeding at an oblique angle to the surface of the workpiece. This zone wherein the metal is sheared (area 1, Fig. 1) is known as the *shear plane.* Fig. 2 is a photomicrograph of a partially formed chip and the line of shear separating the chip from the workpiece is plainly evident. Below the shear plane the micro-structure of the metal is undeformed and undistorted. Above the shear plane it has been distorted by an internal shearing process. In this immediate area the plastic flow characteristics of the metal are of vital concern.

Once the chip is formed it slides over the face of the tool where it encounters frictional resistance, and in this region (area 2, Fig. 1) friction, wear and lubrication are of major interest.

In the region of the finished surface (area 3,



From Metal Cutting Principles, 1952 by M. C. Shaw of M.I.T.

Figure 2 — Photomicrograph of a partially formed chip. See discussion page 82, above.

Fig. 1) the surface and subsurface characteristics of the machined metals are of particular concern.

Three Types of Chips

The same two physical processes — shearing of the metal to form the chip and movement of the chip up the face of the tool — seem to occur in all types of operations, whether they be turning, milling, broaching, drilling, planing, etc. It has also been established that the chip formed may be one of three distinct types, depending upon the material being machined and the conditions under which it is formed. In Fig. 3 photographs are presented showing these three types of chips.

When brittle materials are machined, or when certain ductile materials are cut at low speeds, the metal cannot undergo the required amount of shear without rupturing, resulting in the formation of type 1, a discontinuous chip. Fig. 3 (top) shows the chip to consist of individual segments, loosely joined to each other. In some instances complete rupture occurs at the shear plane, and in these cases a crack frequently is visible ahead of the tool along the shear plane. If this type of chip is the result of machining a brittle metal, the power consumption will be low, tool life will be reasonable and the finish of the machined surface will be fair. When a type 1 chip is formed from machining a ductile material, it is usually accompanied by poor surface finish and excessive tool wear.

The type 2 chip (Fig. 3 center) occurs when the metal is continuously deformed without rupture and flows smoothly up the tool face. This chip is most desirable from the standpoint of surface finish, tool life and power consumption and is associated with relatively low friction between the chip and the tool face. It is usually obtained when ductile materials are machined at cutting speeds in excess of 200 ft./min., or by the use of effective cutting fluids.

The third type of chip (Fig. 3, bottom) occurs when a type 2 chip is formed under such conditions that very high frictional resistance is encountered as the chip moves up the face of the tool, causing some of the metal to shear away from the body of the chip and remain on the tool face, resulting in a "built-up edge."

An understanding of what takes place in each of the three significant areas identified in Fig. 1 involves the knowledge of several fields of engineering and science. It is beyond the scope of this discussion to elaborate quantitatively and in detail on all of the factors which are now known to have an effect in these three regions. Rather, it is the intention to touch briefly on a few of the concepts which currently seem to be most significant.

Shear Angle — An Important Variable

One of the most important factors in the cutting operation is the shear angle. This is the angle formed at the intersection of the shear plane and the direction of the cutting tool or the surface of the work material, and the amount of metal deformed in the formation of the chip depends upon the size of this angle, as illustrated in Fig. 4. When the shear angle is small, the path of shear is long, the amount of metal deformed is large, and the resulting chip is short and thick. Conversely, when the shear angle is large, the path of the shear is short, the amount of metal

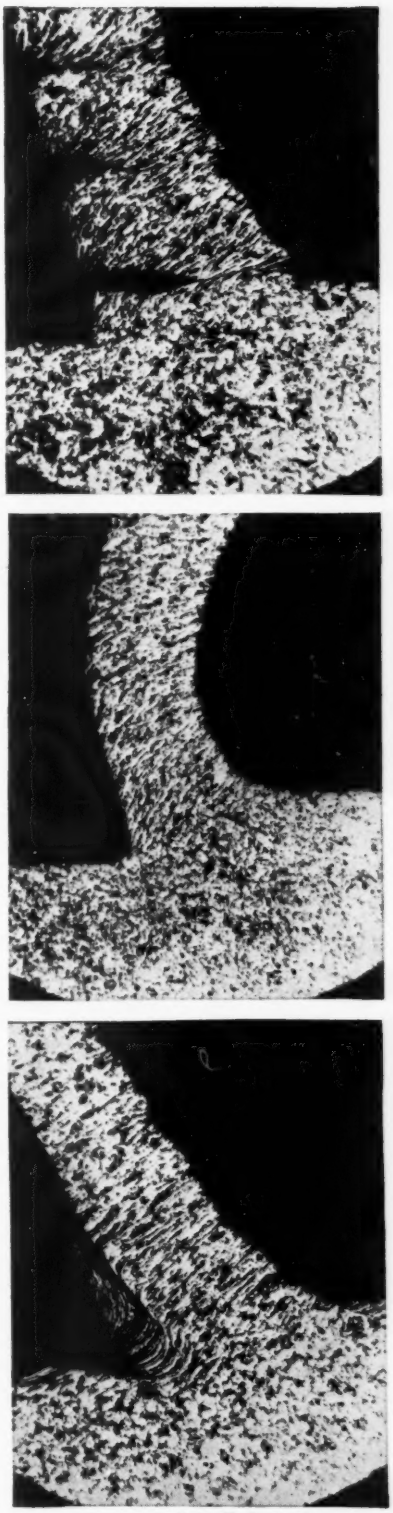
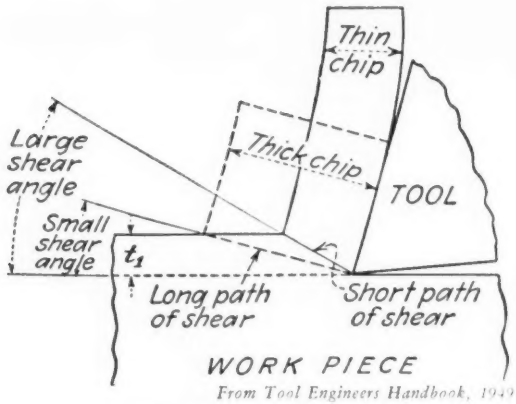


Figure 3 — Three types of chips. See discussion.

From U. S. Air Force Machinability Report, 1950



From Tool Engineers Handbook, 1949

Figure 4 — Effect of shear angle size. See discussion pages 83, and 84 below.

deformed is small, and the chip is long and thin. For optimum machinability a large shear angle is desirable. The shear angle is not a constant quantity but varies over a wide range with the cutting conditions and the properties of the metal being machined. It is a measurable quantity for any given operation, but as yet can not be predicted in advance since all of the factors involved have not been established.

Three Basic Mechanical Variables

Through the use of suitable dynamometers, all of the important forces and energy relationships for any given cutting operation can now be determined, thus making it possible to evaluate practical machining operations and machining characteristics of work materials in terms of basic physical quantities. Fundamental work along these lines has led to the discovery and isolation of three basic mechanical variables, namely shear strength, coefficient of friction and machining constant, which are of prime importance relative to controlling the geometry and forces involved in the formation of the chip.

The *shear strength* is equivalent to the mean shear strength of the metal being cut and is generally high for strong, hard materials and low for weak, soft metals. If a metal is hardened and strengthened by the use of a heat-treating procedure, its mean shear strength will usually increase. On the other hand, hardening and strengthening the metal by cold-working methods will cause little increase in the value of the mean shear strength.

The *coefficient of friction* is a measure of the resistance to sliding encountered by the chip as it passes over the face of the tool, and it is the variable which so far has been most subject to control. It may be reduced by any of several means including an improvement in surface finish of the tool face, a change in microstructure of the metal, a change in tool material, an increase in cutting speed, the addition of free machining additives to the metal, or by the use of cutting fluids.

The *machining constant* is a value derived from the relationship of the compressive strength of a metal to its shear strength, and it appears to be a sufficiently good constant to justify its use in comparing the machinability of various materials. It is not greatly affected by cutting conditions but seems to be directly related to the microstructure and grain size of the metal.

From the standpoint of efficient and economical machining operations, low values of shear strength and coefficient of friction, and high values of the machining constant are desirable.

As is undoubtedly apparent, the total work performed by a cutting tool in removing metal is the sum of the work required to shear the metal plus that used in overcoming the friction at the tool face. However, shear and friction are not mutually independent, and usually any factor which affects one of these quantities will likewise affect the other in the same manner. For example, when the coefficient of friction is decreased, not only will there be a decrease in the work of friction, but due to the formation of a larger shear angle and the corresponding decrease in the amount of metal deformed, there will also be a reduction in the work of shear.

Surface Finish

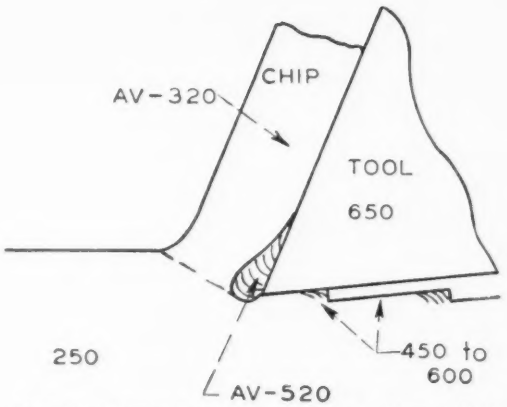
Since the surface finish of the machined metal is an important consideration in machinability, it is perhaps in order to summarize the effect of some of the factors that are known to influence it. Formerly the quality of the finished surface was rated entirely by simple visual inspection. Now however, with the adoption of a measurable unit — the micro-inch — by the use of a profilometer which can record the peaks and valleys of the surface, and with the aid of transparent plastic films by means of which complete permanent visible records of all surface imperfections can be obtained, the nature of the surface can be defined and described much more accurately.

Table I summarizes the general relationship between the nature of the chip and the quality of the surface of the machined metal. The best finish is usually obtained with the continuous chip of low frictional resistance (Type 2), and the worst finish generally results from the continuous chip of high frictional resistance (Type 3).

Of the three basic mechanical variables previously discussed, only the coefficient of friction is known to have an effect on the surface finish. A reduction in the value of this variable will be accompanied by an improvement in the surface of the machined metal.

Another factor which has a great effect on the

surface finish is the strain hardenability of the metal. A material which can undergo deformation and distortion without strain hardening is know as an ideal plastic. However, all engineering metals upon being internally sheared and deformed will strain harden, with the result that the chip and the region near the surface of the machined metal will be harder than the original material. A typical example of this phenomenon is shown in Fig. 5. The tendency for a metal to undergo strain hardening is sometimes expressed by a quantity known as the *Meyer Hardness Exponent*. Increasing values of this quantity indicate a greater tendency for the metal to strain harden. It has been observed that the quality of the finished surface varies inversely with the Meyer Exponent, and thus strain hardenability might be considered as another basic mechanical variable having a direct influence on machinability.



From Metal Cutting Principles, 1952 by M. C. Shaw of M.I.T.

Figure 5 — Representative Brinell hardness values in chip, built-up edge, and finished surface.

TOOL LIFE

Increasing production and reducing costs are largely contingent upon the possibility of increasing tool life, and consequently from a practical standpoint this might be considered the most important of the factors which enter into machinability considerations. The life of a tool is usually measured in terms of the volume of metal removed before it must be reground, and it varies with cutting speeds and feeds, as well as with the nature of the metal being machined.

A cutting tool may fail (1) by breaking or chipping due to faulty design or application, (2) by wearing out or (3) by being overheated. The first of these is strictly mechanical in nature and will not be discussed further.

Tool Wear

Wear of a cutting tool occurs in two regions — on tool face or the area in contact with the chip and on the clearance side of the tool or the region where the tool is in contact with the finished surface. Wear at the tool face usually occurs some distance from the cutting edge and is known as "cratering". Wear on the clearance face begins at the cutting edge and is referred to as a "wear land".

In general all tool wear may be attributed to two basic causes:

1. Wear due to the plowing or abrasive action of the carbides or other hard particles in the work piece.
2. Wear resulting from instantaneous welds that occur when the chip and finished surface slide over the tool faces.

The plowing or abrasive action may be regarded as a secondary cutting operation, and the rate of wear depends upon the size and number of hard particles in the metal and the relative hardness of the tool and the work piece.

Relative to the wear resulting from welding, there appear to be two types of welds which may occur, namely, pressure welds and temperature welds. The former occur at temperatures below and the latter at temperatures above the recrystallization temperature of the metal.

In the machining operation the chip formed is forced against the tool face under extremely high pressures, and if the cutting speeds and resulting temperatures at the chip-tool interface are low, pressure welds can be established. With a weld of this type, the weld interface is stronger than the two metals involved in its formation and when such welds are broken, the rupture occurs somewhere in the bulk of the chip, resulting in a transfer of metal from the chip to the tool face. This of course is the "built-up edge" referred to previously, which forms and breaks down hundreds of times per second and which eventually becomes part of the finished surface. From Fig. 5 it is apparent that as a result of strain hardening the "built-up edge" is much harder than the original metal and

TABLE I

Type of Chip	*Description of Chip*	*Surface Finish*
1	Discontinuous — formed by machining of brittle materials	Good
1	Discontinuous — formed by machining of ductile materials at low speeds	Poor
2	Continuous — low friction between chip and tool face	Best
3	Continuous — high friction between chip and tool face	Worst

this in turn will cause acceleration in the rate of wear due to abrasive action. The abrasion due to the hardening of the chip, the "built-up edge" and the work surface depends upon the initial hardness of the metal, the strain hardenability and the amount of shearing strain involved in the formation of the chip.

The formation of temperature welds occurs without strain hardening, and when the weld is broken, the surfaces separate in the same plane in which they were formed. There is no tendency toward the formation of a "built-up edge", but when the surfaces separate, small particles of the tool matrix may be transferred to the chip. The extent of this transfer-type of wear will depend upon the mean area over which temperature welds occur and the relative strength of the tool and the work piece.

Thus, at very low cutting speeds, the temperatures will be low and the welds formed will all be of the pressure type. As the cutting speed is increased, temperatures will also increase and a point will be reached where temperature welds will begin to form. As cutting speeds are further increased, all of the welds formed will be temperature welds.

Thus, the basic mechanical variables, whose effects on tool wear are known are the shear strength of the metal, the coefficient of friction, the machining constant, the strain hardenability, the initial hardness of the metal and the micro-structure of the metal. The effect of these basic mechanical quantities on forces, surface finish and tool life is shown in Table II.

Tool Life Versus Temperature

Although the exact relationship between temperature, tool life and forces in metal cutting are far from being completely established, there seems to be a direct relationship between the temperature at the chip-tool interface and the tool life. As this temperature increases, the ability of the tool to withstand the forces exerted upon it decreases rapidly. This is illustrated by the graph in Fig. 6, which shows that a very small change in temperature had a very large effect on tool life. Consequently, in the interest of long tool life, it is imperative that the temperature at the chip-tool interface be kept as low as possible.

THE ROLE OF CUTTING FLUIDS IN MACHINING OF METALS

Most of the work performed in a cutting operation is translated into heat, which has just been indicated as being most detrimental to the life of a cutting tool. Thus, any practical means of reducing the flow of heat formed to the tool is, in most cases, very desirable. Likewise, any means of reducing the total amount of heat formed in the cutting process must also be looked upon with favor. Cutting fluids can be effective in both respects. In fact, a cutting fluid can be considered as having two basic functions in the machining process.

1. To serve as a coolant and remove heat from the cutting tool, work piece and chips.
2. To serve as a medium for reducing the friction that occurs as the chip slides up the face of the tool.

A cutting fluid also has another function which frequently is of practical importance, and that is to flush the chips away from the cutting zone.

TABLE II

Effect of Basic Mechanical Quantities on Forces, Surface Finish, and Tool Life

Property of metal being cut	*A decrease in the given property has the following effect:*		
	Known effect on forces and power consumption	*Usual effect on surface finish*	*Probable effect on tool life*
Machining constant, C	Bad	?	Bad
Shear strength S_s	Good	None	Good
Coefficient of friction μ	Good	Good	Good
Hardness, H	*	None	Good
Strain hardenability, n	*	Good	Good
Amount of hard, abrasive inclusions in microstructures	*	None	Good

*Forces and efficiency are determined almost completely by values C, S_s, and μ.

As a Coolant

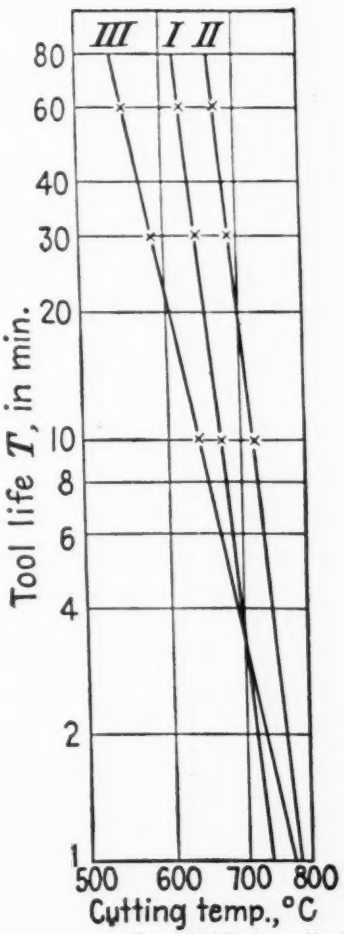
In order for a liquid to be most effective as a coolant it should have a high specific heat and high thermal conductivity. From this standpoint, water is about the most efficient cooling agent known. In comparison with a straight mineral oil, water is about twice as effective for removing heat. However, water has essentially no lubricating properties and in addition it promotes rusting, as a consequence of which it is hardly ever used alone as a cutting fluid. There is a way that lubrication and anti-corrosion properties can be imparted to water, and this is through the use of "soluble oils" or emulsifiable oils. These are oils which have been so compounded that they will mix with water and form stable emulsions thereof which can then be safely employed as a cutting fluid. Since water is the major component of these emulsions, as they are normally used, it still can function as an efficient coolant. However, the mineral oil and the additives contained therein impart desirable lubricating, anti-friction and anti-corrosion properties to the emulsion. It is probably apparent that by altering the ratio of the soluble oil to water, various combinations of cooling and lubricating properties can be imparted to the emulsion. Although the soluble oil-water emulsions are usually employed in operations where cooling is the main requirement, they can also be employed within certain limits in a variety of machining operations.

As a Lubricant

The overall effect of reducing the coefficient of friction between the chip and the tool face has already been mentioned. Not only is there a decrease in the friction work but there is also a reduction in the amount of shear work as well, due to an increase in the shear angle. In addition, a reduction of friction between the chip and the tool will also decrease the tendency toward a "built-up edge" and thereby have a very favorable effect on the finish of the machined metal. Consequently, it is quite apparent that reducing the coefficient of friction has a far-reaching effect in the machining operation.

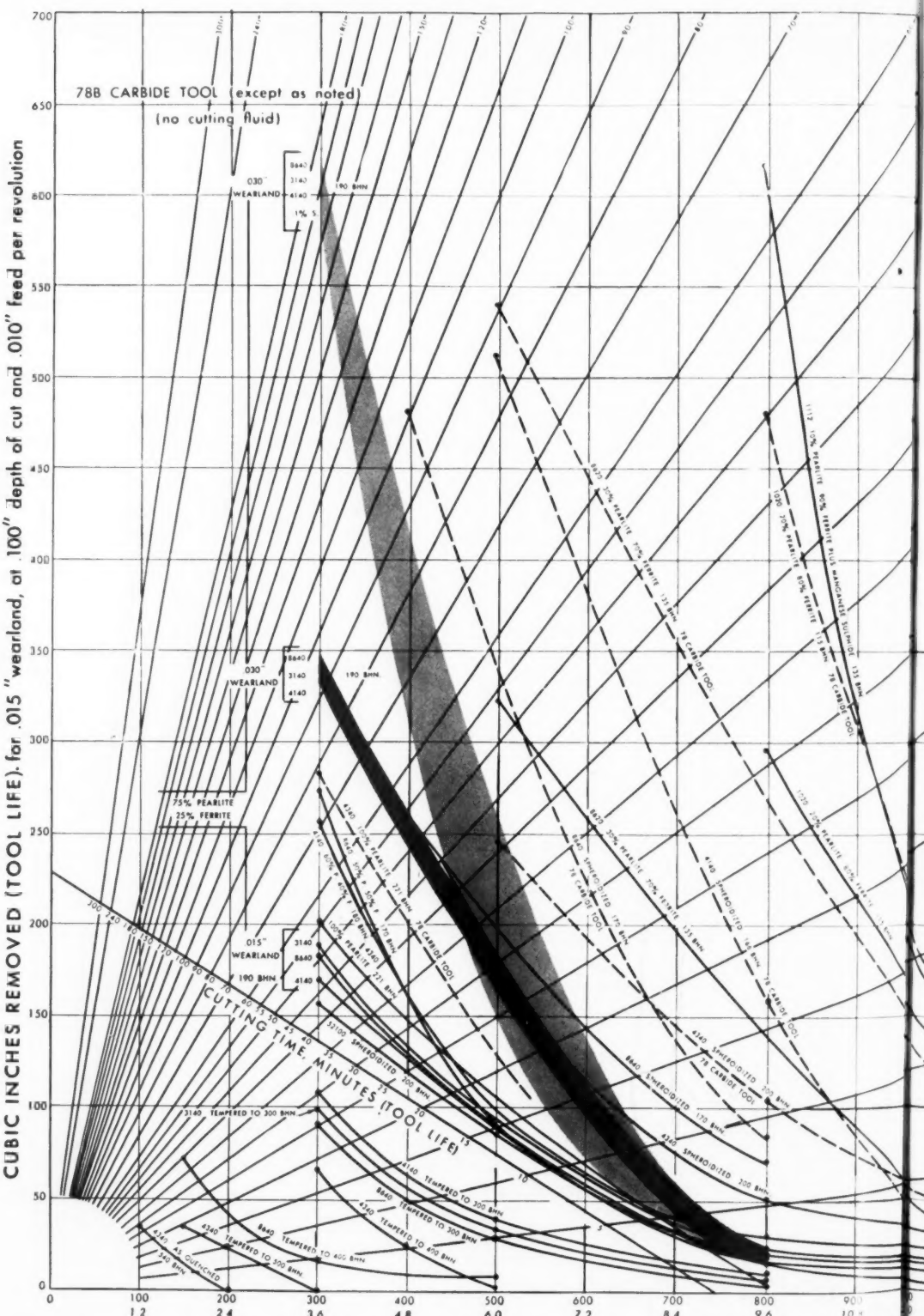
Certain fluids such as lard oil have long been known to have a very favorable effect on tool life and surface finish, even though they are not particularly good coolants. It was generally assumed that such fluids acted merely as lubricants. However, it has since been demonstrated that the pressure at the points where the chip and tool face are in contact are of the order of 100,000 psi, and in addition the temperatures are extremely high. Under such conditions it would be impossible for a fluid to be present at these points, and consequently the explanation for the action of certain fluids in reducing friction in these areas must be different from that of a simple lubricant.

In the first place, in order for a fluid to be effective in lowering the friction, it obviously must penetrate the chip-tool interface, and if the pressures there are of the order of 100,000 psi, one might ask how a fluid can be present in these regions. Actually the surfaces of the chip and the tool are far from being truly smooth, although they may appear so to the eye, and they are in true contact only at scattered points distributed over the apparent area of contact. Consequently, there is a network of minute passages or capillaries into which the fluid or its vapors may be drawn. Fig. 7 is an exaggerated view of the real nature of the chip-tool interface. Because of the partial vacuum in these passages surface tension forces in the fluid and the action of a pressure differential of one atmosphere are sufficient to cause the fluid to



From Tool Engineers Handbook, 1949

Figure 6 — Typical tool-life versus cutting temperature for three different high-speed steels.


78B CARBIDE TOOL (except as noted)
(no cutting fluid)
CUBIC INCHES REMOVED (TOOL LIFE) for .015 "wearland, at .100" depth of cut and .010" feed per revolution
CUTTING TIME, MINUTES (TOOL LIFE)
CUTTING SPEED, FEET
PRODUCTION RATE, CUBIC IN
.030" WEARLAND
.015" WEARLAND
190 BHN
75% PEARLITE
25% FERRITE
8640
3140
4140
4340
700
650
600
550
500
450
400
350
300
250
200
150
100
50
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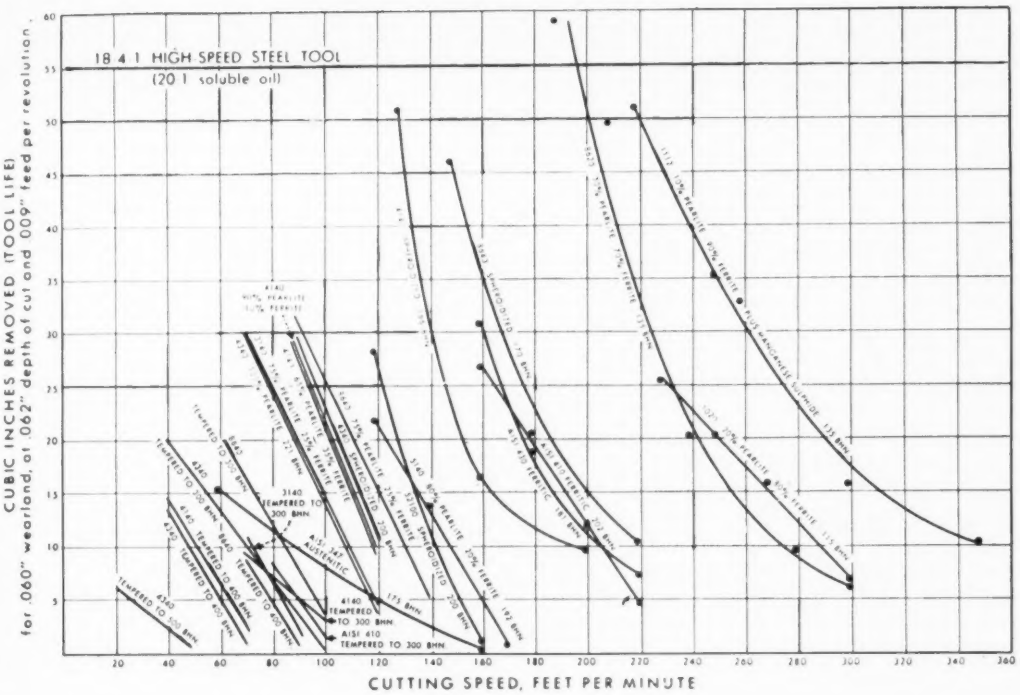
84
96

Figure 10

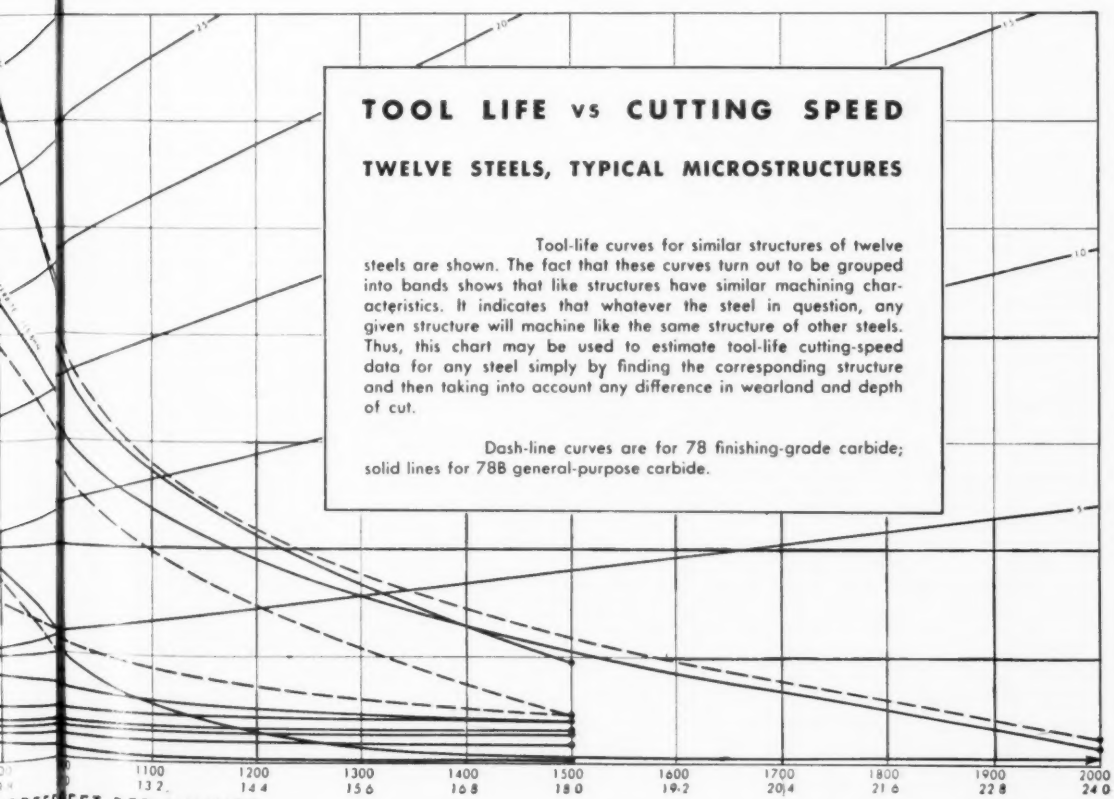

18-4-1 HIGH SPEED STEEL TOOL
(20-1 soluble oil)
CUBIC INCHES REMOVED (TOOL LIFE)
for .060" wearland, at .062" depth of cut and .009" feed per revolution
CUTTING SPEED, FEET PER MINUTE
4140 TEMPERED TO 300 BHN
AISI 610 TEMPERED TO 300 BHN
3140 TEMPERED TO 300 BHN
AISI 347 AUSTENITIC

TOOL LIFE vs CUTTING SPEED

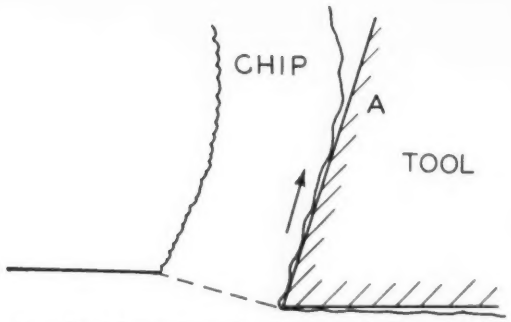
TWELVE STEELS, TYPICAL MICROSTRUCTURES

Tool-life curves for similar structures of twelve steels are shown. The fact that these curves turn out to be grouped into bands shows that like structures have similar machining characteristics. It indicates that whatever the steel in question, any given structure will machine like the same structure of other steels. Thus, this chart may be used to estimate tool-life cutting-speed data for any steel simply by finding the corresponding structure and then taking into account any difference in wearland and depth of cut.

Dash-line curves are for 78 finishing-grade carbide; solid lines for 788 general-purpose carbide.



From U. S. Air Force Machinability Report, 1951



From Metal Cutting Principles, 1952 by M. C. Shaw of M.I.T.

Figure 7 — Exaggerated view of chip-tool interface.

flow through the capillaries and reach the tool point despite the adverse motion of the chip.

Even though the fluid can flow through these fine capillaries, how does it serve to reduce friction? Due to the pressures involved, it certainly can not prevent the metal-to-metal contact at the high points, and these are the areas where friction occurs. Research has now shown that the friction is not reduced by simple lubrication, but the reduction is actually the result of a chemical action. The surface of the chip in contact with the tool face has just been freshly formed from the work piece and consequently it is in a highly reactive state. This condition, in conjunction with the high temperatures and pressures existent at the point of contact of the chip and tool, is very favorable for the production of a chemical reaction. It has been found that in order to be effective for reducing the coefficient of friction, the cutting fluid must contain small amounts of such elements as sulfur, chlorine, phosphorus or fatty acids. These products react with the chip to form metallic compounds, or soaps, in the case of the fatty acids, and thus instead of an actual metal-to-metal contact, the metals are separated by a thin film of a metal compound. Consequently, only the shear strength of this solid layer of metal compound must be overcome rather than the shear strength of the metal junction. If the shear strength of the compound formed is less than that of the metal, there will be a reduction in the coefficient of friction.

For example, both chlorine and sulfur are very effective for reducing the coefficient of friction. The average shear strengths of the stable iron sulfides are about 50% of the shear strength of iron, while the average shear strengths of the iron chlorides are about 20% of that of iron. From this it might be inferred that cutting fluids containing chlorine should be more effective than those containing sulfur, and under certain conditions that is true. At low cutting speeds where the temperatures at the chip-tool interface are relatively low, some chlorinated fluids are more effective in reducing friction than are sulfurized fluids. On the other hand, the iron sulfides have much higher melting points than the chlorides. Consequently, as the cutting speeds are increased and the temperatures go up, the sulfurized fluids become increasingly more effective than the chlorinated fluids.

Since the reduction of friction is the result of chemical action, there obviously must be a sufficient amount of time for the reaction to occur. Thus as cutting speeds approach high values, and the time of contact becomes less, it is increasingly difficult for a fluid to reduce the friction.

From the foregoing discussion it should be readily apparent that cutting fluids play a major role in machining operations. Were it not for the fact that suitable fluids are available, which, when properly used, will result in substantial increases in tool life and improvement of the surface finish of the machined metal, it can safely be stated that the metal cutting industry, as we know it today, could not exist. The availability of fluids which exert such a favorable effect on the overall metal cutting operations is not mere coincidence. The bulk of these products are supplied by petroleum companies who, in cooperation with the metal cutting industry, have poured vast quantities of research dollars and hours into their development. Great strides have already been made in the development of effective cutting fluids. However, much of the challenge which the metal cutting industries currently face is being passed on to the petroleum companies, and pressure is being exerted from all sides for the development of new and better cutting fluids.

MICROSTRUCTURE AND MACHINABILITY

Until very recently little has been done to apply metallurgical knowledge to the improvement of machining conditions. However, it is now recognized that tool life and surface finish are directly related to the microstructure of the metal being machined. Materials having similar metallurgical structures will likewise have similar machining characteristics, regardless of their relative physical and chemical properties. On the other hand, it has been shown that slight variations in the microstructure within a single piece of stock can cause as much as a five-fold change in tool life at a given set of conditions. Specific treatment and control of the work metal before machining has been seriously neglected. However, on the basis of current information it is now apparent that far closer scrutiny of the microstructure is needed, and more important, once the optimum microstructure is known, close control in the processing of the metal is required in order that the microstructure desired be produced.

What Is Microstructure

Pure metals consist of individual microstructures or grains of a single constituent. Metal alloys, on the other hand, are composed of individual grains of one or more constituents. The ultimate strength and hardness of the metal or alloy depends on the number and size of these grains, which in turn are dependent upon the chemical composition of the alloy and the heat treatment and mechanical processing to which it is subjected.

Some of the individual microstructures found in steels and cast irons are identified as follows.

Austenite
—a non-magnetic form of iron having a high solubility for carbon. Since the carbon present is mostly dissolved, this phase is known as a solid-solution matrix. It is present when steels are brought up to the proper temperature for rolling, forging or quenching, but in the ordinary carbon steels it is unstable below 1300°F. and thus does not exist at room temperature. The presence of alloying elements in a steel increases the low temperature stability of this phase, and in highly alloyed steels a 100% austenitic structure is possible at room temperature.

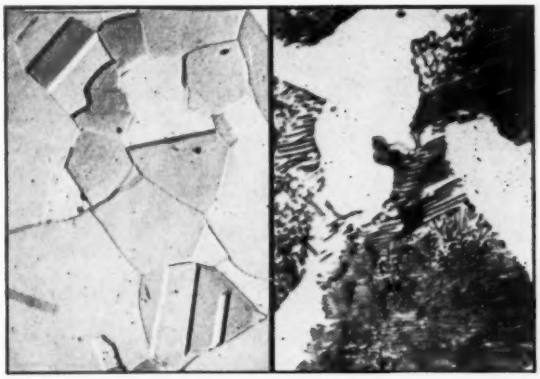
Ferrite
—a magnetic form of iron having low solubility for carbon. It is present in the free form in most low carbon steels and also exists under certain conditions in medium carbon steels, provided they have been cooled slowly.

Cementite
—an intermediate compound of definite lattice arrangement corresponding to the formula Fe_3C. This compound is very hard and abrasive and its presence in ordinary steels indicates a lack of control during heat treatment. It is usually present in high carbon steels and in these materials it is essential that the cementite grains be uniformly distributed.

The above three phases may be considered as the basic microstructures present in steels and cast irons and all of the other known phases are the result of some combination of these three.

Pearlite
—a lamellar structure consisting of alternate layers of ferrite and cementite. The pearlite grains may be coarse or fine and the space between the layers may be wide or narrow. In carbon steels the presence of this phase increases with the carbon content of the steel. The pearlite grain size depends upon the cooling rate.

Spheroidite
—a structure consisting of large globules of cementite in a ferrite matrix. This structure can be produced by proper heat treatment of pearlite or by very slow cooling of a carbon steel.



Courtesy of United States Steel Company Research Laboratory
Left — Austenite
Right — Pearlite and Ferrite

Widmanstatten
—a cross-hatched, needle-like structure of ferrite needles in fine pearlite. It results from cooling at a critical rate from an extremely high temperature such as those encountered in forging and rolling.

Martensite
—a distorted form of ferrite obtained when steel is quenched or cooled at a rapid rate from its austenitic temperature. It is hard and brittle, having a needle-like appearance, and is rarely used in engineering applications in its martensitic form. Steels having this structure are ordinarily tempered to improve their physical properties. During the tempering operation, the ferrite is transformed to a more stable form and the excess carbon precipitates as cementite.

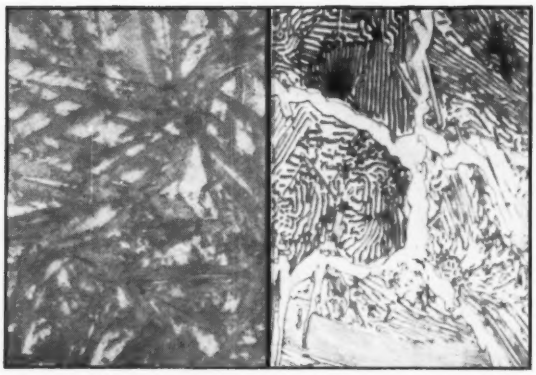
Bainite
—a feathery combination of ferrite and cementite occurring in steels which have been isothermally treated in the temperature ranges of 480-1100°F.

Free Graphite
— is present in cast iron in either a flaky form, as in the common gray variety of cast iron, or in nodules as in the malleable irons.

Steadite
—a compound of iron, phosphorus and carbon found only in cast irons. It has the lowest melting point of all the constituents which may be present in cast iron.

White Iron
—a structure of 50% free pearlite and 50% cementite formed in cast irons when they are cooled at an extreme rate from their molten condition.

The microstructures of metals and alloys depend on their chemical composition and their heat treatments. For any cast iron, carbon steel or alloy of a given composition, a variety of microstructures can be obtained simply by slight variations in the heat treatment involved in their preparation. The time-



Courtesy of United States Steel Company Research Laboratory

Left — Martensite
Right — Pearlite and Cementite

temperature relationships in the heat treatments are particularly critical. For example, when a steel is in the austenitic phase, at high temperature, the carbon present is in solution. When the temperature is reduced, the solubility of the carbon decreases and it precipitates out as cementite in the case of carbon steels, and as cementite plus other metal carbides in the case of alloyed steels. These carbides are very hard, and the hardness and the strength of the steel depends upon their number and their size. Rapid cooling from the austenitic temperature results in the formation of small, closely packed carbide particles which are associated with a strong, hard steel. Slow cooling favors the formation of larger, more widely spaced carbide particles and a structure of this nature is softer and weaker. It has been shown that the relative shape of the carbide particles has little effect on the physical properties of the metal, the determining factor being their number and their relative spacing.

CAST IRON

Cast iron is an iron alloy containing from 2 to 4% carbon in the form of graphite, and it may assume many characteristic structures. If it is cooled rapidly, white iron is obtained which consists of 50% pearlite and 50% cementite and which is extremely hard. If the cast iron is cooled slowly, the common gray form is produced consisting of graphite flakes in pearlite. Other structures such as free ferrite, steadite and inclusions of sand and slag also are sometimes present. Free ferrite, if present in an amount greater than 10%, lowers the strength of the iron.

Malleable cast iron is formed by slowly heating white iron to 1600°F., maintaining it at this temperature for a considerable period of time, and then slowly cooling. By this process the cementite is converted to graphite and austenite, and upon cooling small nodules of graphite are deposited in a ferrite matrix. This form of iron is extremely tough.

In the machining of cast irons the graphite present has an internal lubrication effect and thus reduces the tendency toward the formation of a "built-up edge". In addition, the graphite particles serve to make the iron relatively weak in tension but provide a multitude of points of high stress concentration. This results in a periodic brittle fracture and the chips formed are usually of the discontinuous type. The presence of steadite in cast iron has been found to have an adverse effect on tool life only if present in amounts larger than 10%. On the other hand, free carbides, if present in quantities as low as 5%, are very undesirable, and when present in large amounts, as in white iron, it is almost impossible to machine the metal except by grinding. The relative tool life to be expected from structures frequently found in cast iron is shown in Table III. These estimates were made from data obtained with carbide cutters at cutting speeds in excess of 300 ft. per minute.

Fig. 8 shows the tool life as a function of cutting speeds for four major cast iron structures. These data were obtained in tests conducted on a fixed-bed milling machine with a single-tooth cutter, using a carboloy 44A carbide tipped face mill, a depth of cut of .187 inches and a feed of .015 inches. Tool life is expressed as the volume of metal removed for a .030 inch tool wear. An inspection of this chart shows that for all microstructures the greatest tool life is obtained at a cutting speed of about 300 ft. per min. Below this speed, tool wear is not uniform and localized wear shortens the tool life. It is interesting to notice the great difference in the machining characteristics of the ferrite structure as compared to the pearlite irons.

In the practical application of this chart, it is necessary only to determine the microstructure of the metal that is to be machined, calculate the volume of metal removed per tooth and decide on the cutter life-machining rate combination that affords maximum production at minimum cost.

As an example, assume that there are 1,000 pieces 5 in. wide by 16 in. long that must be milled $\frac{1}{8}$ in. deep. This means that a total of 10,000 cu. in. of metal must be removed. If the cutter to be used has 20 teeth, then each tooth would remove 500 cu. in. of metal. The chart shown in Fig. 8 is plotted for a depth of $\frac{3}{16}$ in. while the hypothetical job in question requires a $\frac{1}{8}$ or $\frac{2}{16}$ in. depth. Therefore, the value of the metal removed ordinate must be multiplied by $\frac{2}{3}$ to suit the new depth of cut. $500 \times \frac{2}{3} = 333$. Also assume that coarse pearlite is to be machined. Thus, by looking at the chart, it may be seen that the whole job can be cut without tool resharpening at a speed slightly greater than 300 ft. per min. It is also evident that if the metal could be economically transformed into the ferrite

TABLE III

Tool Life Index Numbers for Typical Flake-Graphite Cast Iron Microstructures

Structure	*Brinnel Hardness*	*Index Number*
Ferrite, graphite (Full anneal)	120	20
50% ferrite, 50% graphite (Partial anneal)	150	10
Coarse pearlite, graphite	195	2
Medium pearlite, graphite	215	1.5
Fine pearlite, graphite	218	1
Fine pearlite, 5% Steadite graphite	197	1
Fine pearlite, 5% free carbide, graphite	240	0.3
White iron	over 500	

condition, a cutting speed of 900 ft. per min. could be used.

For a given cast iron and cutter it was observed that surface finish improves as the cutting speed is increased. Also, at a constant cutting speed, surface finish improves with iron of finer structures, especially as the quantity of free graphite decreases.

With regard to machining power, it was observed that the unit power, expressed as horsepower per cu. in. per minute, was about the same for all ordinary pearlitic cast irons but was considerably less for the ferritic iron. The power required increased as much as three times as the cutting tool became dull.

Studies have also been made to compare the machining characteristics of the common gray cast irons which contain flake graphite with the malleable cast irons containing nodular graphite. The tests were conducted in a turning operation using a Kennametal K-6 carbide cutter, a .100 in. depth of cut and a feed of .01 in. per revolution. The tool life end point selected for the test was .030 in. of wear.

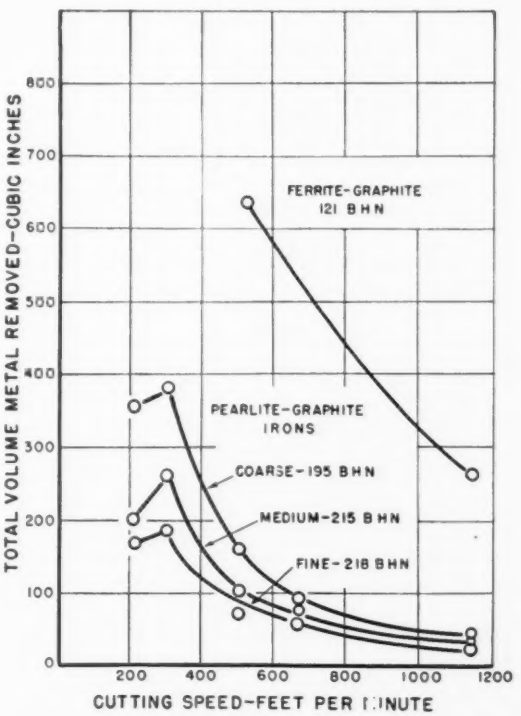
Fig. 9 shows the relationships between cutting speed and volume of metal removed for three flake graphite and for four nodular cast irons. It is noteworthy to observe that the weakest nodular graphite iron is stronger than the strongest flake graphite iron (70,000 p.s.i. against 59,000 p.s.i.) but the nodular iron permits a cutting speed of 970 f.p.m. for a 200 cu. in. tool life, while the flake graphite iron allows a speed of only 150 f.p.m.

STEELS

Plain carbon steels are basically alloys of iron and carbon having a wide range of hardness values due to the carbon present and the manner in which it is associated with the iron. For machinability considerations the carbon steels can be divided into three groups according to their carbon content: (1) low-carbon steels containing less than 0.2% carbon; (2) medium-carbon steels containing from 0.2 to 0.5% carbon; and (3) high-carbon steels containing more than 0.5% carbon.

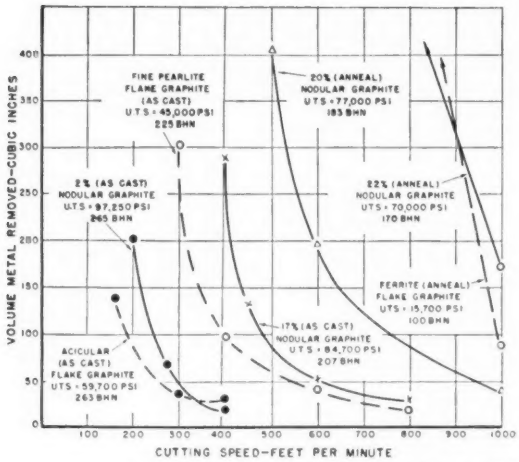
The low-carbon steels have structures ranging from 70 to 85% free ferrite and 15 to 30% pearlite. They are similar to pure iron in that they have poor machining characteristics and little can be done to improve their machinability, other than the addition of free machining agents such as sulfur or lead. In machining these metals, which are relatively soft, high cutting speeds should be used so as to favor the formation of temperature welds.

The medium and high carbon steels are capable of assuming a wide variety of structures depending on the rate at which they are cooled. For example, an annealed steel containing 0.40 to 0.50% carbon may have any one or combinations of the following structures: (1) 90% pearlite—10% free ferrite; (2) 50% pearlite—50% blocky free ferrite; (3) Widmanstatten; and (4) spheroidized. In these steels the machining characteristics are definitely influenced by the metallographic structure. From the standpoint of minimizing pressure welding and



From U. S. Air Force Machinability Report, 1950

Figure 8 — Tool-life curves for indicated cast iron microstructures.


VOLUME METAL REMOVED—CUBIC INCHES
CUTTING SPEED—FEET PER MINUTE
FINE PEARLITE FLAKE GRAPHITE (AS CAST) U.T.S.=45,000 PSI 225 BHN
2% (AS CAST) NODULAR GRAPHITE U.T.S.=97,250 PSI 265 BHN
ACICULAR (AS CAST) FLAKE GRAPHITE U.T.S.=59,700 PSI 263 BHN
20% (ANNEAL) NODULAR GRAPHITE U.T.S.=77,000 PSI 183 BHN
22% (ANNEAL) NODULAR GRAPHITE U.T.S.=70,000 PSI 170 BHN
17% (AS CAST) NODULAR GRAPHITE U.T.S.=84,700 PSI 207 BHN
FERRITE (ANNEAL) FLAKE GRAPHITE U.T.S.=15,700 PSI 100 BHN

From U. S. Air Force Machinability Report, 1950

Figure 9 — Comparison of tool-life curves for indicated flake graphite and nodular graphite cast irons.

"built-up edge" formation, it is desirable to have as hard a structure as possible. Such a structure is associated with a small mean ferrite path and wide dispersion of the carbide particles. However, from the standpoint of decreased hard particle wear, it is advisable that the specific area of the exposed carbide surface be as small as possible. This requires relatively few, widely spaced, carbides. Obviously, these two requirements are opposed to each other and hence an optimum mean ferrite path will exist, and this optimum will shift in the direction of a greater mean ferrité path as the carbon content of the steel is increased.

In alloy steels, elements other than carbon are used for various purposes, and they may be considered to perform their functions by one or more of three basic means.

1. By forming carbides that are insoluble in ferrite (tungsten, molybdenum, vanadium, chromium).
2. By going into solution in the ferrite matrix (silicon, manganese, nickel, cobalt and chromium).
3. By forming inclusions which are insoluble in ferrite (silicon, aluminum, titanium, manganese, sulfur, phosphorus and lead).

Just as the presence of carbon complicates the picture of pure metals, the presence of alloying elements complicates the picture of plain carbon steel. All of the alloying elements that are found in steel are generally undesirable from the standpoint of tool wear. Those elements which form additional hard carbides, such as vanadium, tungsten, chromium and molybdenum, cause a significant increase in the hard particle plowing wear. Those elements which go into solid solution generally cause an increase in the hardness of the matrix and also increase the tendency of the matrix to strain-harden. Nickel is particularly troublesome in this respect. The "built-up edge" that is formed will be harder, which in turn will cause greater plowing wear. The increased hardness of the matrix will also cause an increase in transfer wear since the hardness of the tool and the work piece will be more nearly equal, and consequently there will be a greater tendency for particles to be plucked from the surface of the tool as the temperature welds come apart. While fewer pressure welds might be expected in the alloy steels as a result of the harder matrixes, the welds which are formed give rise to larger built-up appendages as a result of the increased strength of the more highly strain-hardened material in the "built-up edge."

Fig. 10 is a self-explanatory chart summarizing a vast amount of data obtained from machining twelve commonly used steels ranging from low-carbon steel to the high-carbon ball bearing steels and stainless steels. The data from which this chart was prepared were obtained using both 78B and 78 carbide tools and a 18:4:1 high-speed steel tool. The conditions used for these machining studies are included in the chart. This graph is by no means limited to the test conditions or the materials shown. In order to predict tool life at any desired cutting speed with any steel, whether or not it is on the chart, it is only necessary to compare the microsctructures and hardness with the nearest corresponding test example.

Data have been extracted from Fig. 10 and presented in Table IV to illustrate how the machining properties of a given metal are influenced by its microstructure. This table shows how the speeds required to cut a constant volume of metal and how the volume of metal cut at a constant speed vary with the microstructure of 8640 steel when using a 78B carbide tool to a .015 wear land. Of particular note is the difference of cutting speeds between the spheroidized and the 50-50 pearlite-ferrite structure although they both have the same Brinnel hardness.

HIGH TEMPERATURE CORROSION RESISTANT ALLOYS

The sudden demand for jet engines and turbines in large quantities and at reasonable prices has presented the metal cutting industry with one of its greatest challenges. In order to withstand the high forces and chemical attacks at the high temperatures to which they are subjected, these turbines and engines must be fabricated from highly alloyed metals which are extremely difficult to machine. There appear to be three major reasons for the difficulties encountered in the machining of these materials: (1) they exhibit extremely high shear strength during cutting; (2) they have a high capacity for strain

hardening; and (3) their microstructures due to strain hardening and the presence of precipitated carbides are highly abrasive.

Most of the variables in the machining process have been found to be especially critical in the case of these jet engine alloys. Acceptable tool life and production rates can be obtained only if the microstructures, feeds and speeds, and tool materials are carefully selected.

Data are available from machining studies made on six alloys representative of those used in the manufacture of jet engines, including S-816, Inconel-X, Timken 16-25-6, AISI 347, AISI 4340 and AISI 410. The tests were made on two different lathes, using various carbide tools. The depth of cut for all tests was .026 inches and the tool life was based on a wear land of 0.16 inches for the S-816 and the Inconel-X alloys and .008 inches for the other materials.

S-816 and Inconel-X are typical of the alloys employed in the manufacture of the turbine buckets. The former is essentially an alloy of 20% chromium-20% nickel-40% cobalt and the latter is one of 15% chromium and 73% nickel. Alloys of this nature cannot be hardened by the procedures commonly employed for carbon steels since they retain their matrix structure over a wide temperature range. Consequently, the attainment of maximum hardness and strength requires a series of heat treatments and in some cases mechanical working. Solution treatment is the first step in hardening the bucket alloys. This involves heating the material to 2100°F. to dissolve the carbides and form a single solid solution. The parts are then quenched in either air or water depending upon the particular alloy involved. Although the solid solution remains after quenching, it is unstable and eventually the carbides will again precipitate and harden the alloys. Age hardening can be quickly accomplished by reheating the quenched metal to about 1400°F.

Timken alloy, containing 16% chromium, 25% nickel, 6% molybdenum and the balance iron, is used in jet engines in the work hardened condition for the turbine disk.

AISI 347 is an 18% chromium-10% nickel stainless steel consisting of austenite.

AISI 4340 is the high strength alloy steel used for the turbine shaft.

AISI 410, a 12% chromium stainless steel which can be basically ferritic or martensitic, is used in the tempered condition for compressor blades and the compressor rotor in jet engines.

The chart shown in Fig. 11 compares the tool life and production rate attainable with the bucket materials, the turbine disk alloy, the stainless steels and the high strength alloy steel used for the turbine shaft as determined in these machinability studies. This chart shows each alloy to best advantage in that the curves for the individual alloys are those obtained using the best tool material, the optimum feed and speed and the most machinable structure.

For the turbine bucket alloys, Inconel-X and S-816, solution treatment and the use of cast iron grade of cutting tool rather than the steel cutting grades permit longer tool life. The feed was found to be critical and for both materials it should be between .008 and .014 in. per revolution. The optimum cutting speed and the greatest tool life is about 50 f.p.m. for both of the alloys.

Regarding the Timken alloy, it was found that tool life improved considerably in going from the hardened condition to the stress-relieved state and even more so when the alloy was solution treated. Like the bucket alloys, the best tool life was obtained in the range of .011 to .014 in. per revolution. However, the problem of machining Timken alloy is not nearly as difficult as that involved with the bucket alloys and fair tool life can be obtained with cutting speeds up to 300 f.p.m.

The three remaining alloys machined with far greater ease than the three just discussed. The machining properties of 347 stainless and 4340 were found to be sufficiently good that a cutting speed of 400 f.p.m. could be recommended for production turning. With the 410 stainless in the tempered form, used in the manufacture of the compressor rotor and blades, it may be observed from the chart that machining speeds of the order of 600 f.p.m. could be used.

Thus in machining these jet engine alloys, par-

TABLE IV

Relationship Between Microstructures of 8640 Steel and Machinability, Using a 78B Carbide Tool

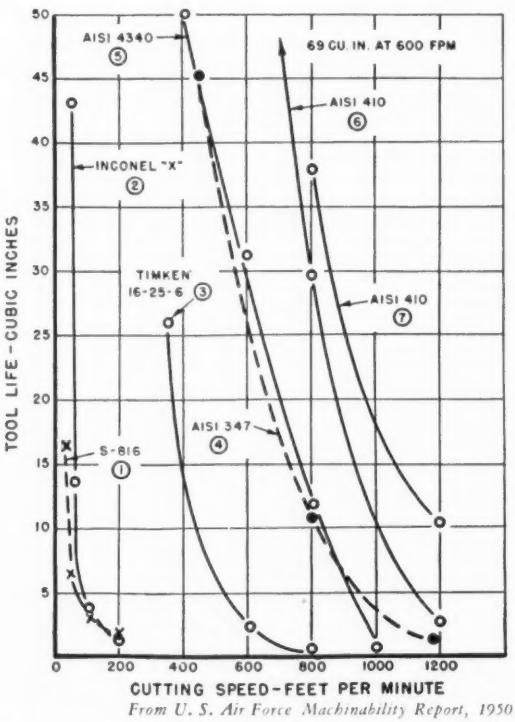
Structure	*Hardness*	*Cutting Speed To Remove 100 Cu. In.*	*Cu. In. Removed at 300 F.P.M.*
Spheroidized	170	705	—
50% Pearlite — 50% ferrite	170	490	275
75% Pearlite — 25% ferrite	190	475	185
Tempered	300	290	93
Tempered	400	120	18

ticularly the bucket materials, the first step should be to plan the sequence of manufacturing operations, if possible, so that all of the major rough machining operations may be performed with the solution treated form, leaving only a minimum of stock for finish grinding. The second step is to use the best carbide available pending the development of better tool materials. Finally, tool life will be satisfactory only if the best feeds and speeds are used.

MACHINING TITANIUM

It appears that titanium alloys may cut eventually into the fields now dominated by aluminum alloys, steel and stainless steel. As might be expected, any new material requires a vast amount of development work and shop experience and it will probably be some time before the ultimate potentialities can become reasonably stabilized.

Titanium is a silvery gray metal weighing about half as much as steel or about one and a half times as much as aluminum. It has excellent corrosion resistance and exceeds all of the usual materials in its high strength-weight ratio. Titanium alloys retain their strength at temperatures up to about 800°F., and their endurance limits and fatigue characteristics appear to be excellent.



From U. S. Air Force Machinability Report, 1950

Figure 11 — Tool-life curves for indicated high-temperature alloys.

COMPARATIVE CUTTING SPEEDS FOR 30 cu. in. TOOL LIFE at .008 WEAR

1	S-816	sol. treated	35fpm
2	Inconel "X"	sol. treated	50fpm
3	16-25-6	stress rel'd	350fpm
4	AISI 347	annealed	550fpm
5	AISI 4340	300 Brinell	600fpm
6	AISI 410	306 Brinell	800fpm
7	AISI 410	204 Brinell	850fpm

Feed per rev: .009-.011 in.; 1 and 2, K6 carbides; 3-7, K3H carbide; same tool angles all tests; no cutting fluid.

The machining of titanium so far has been found to be as difficult, if not more so, than the machining of the high temperature jet engine alloys. The very poor tool life that is obtained when titanium is machined is being attributed to the high solubility of the metal. It alloys very easily with other materials and it appears as though the tool material is actually dissolved away when titanium is cut.

Available data indicate that in turning operations with high speed steel tools, a tool life of nine cubic inches can be obtained at a cutting speed of 40 f.p.m., a depth of cut of .062 in. and a feed revolution of .009 in. With the cast iron grades of carbide, a tool life of ten cubic inches can be obtained, at a cutting speed of 200 f.p.m. and a feed per revolution of .012 in.

A considerable amount of basic work investigating the machining characteristics of titanium is currently being performed by various groups, and in the near future more information should be available than there is at the present time.

SUMMARY

Metal cutting has long been an art, but now through the combined efforts of the physicist, the chemist, the metallurgist and the engineer, it is currently in the process of being transformed into a science. Great strides have already been made in establishing some of the basic principles and underlying laws that govern the cutting and machining of metals. Although the story of metal cutting is far from being complete and much additional basic work still remains to be done, fundamental information is being accumulated at such a rapid rate that it appears the time is not far off when all of the variables that influence the operation will be identified and their inter-relationships established.

One of the major factors contributing to the overall advancement and progress of the metal cutting industry has been the availability of high quality cutting fluids. By the proper use of a suitable fluid substantial increases in tool life and improvements in surface finish can be realized, both of which are of paramount economical importance to the industry. Most of these cutting fluids are supplied by the petroleum industry, and they represent years of continuous research and development. Current demands on the metal cutting industry are greater than ever before and the ultimate success in meeting the challenge will be contingent in a large measure upon the petroleum companies furnishing larger quantities of even higher quality cutting fluids.

Printed in U. S. A. by
Salley & Collins, Inc.
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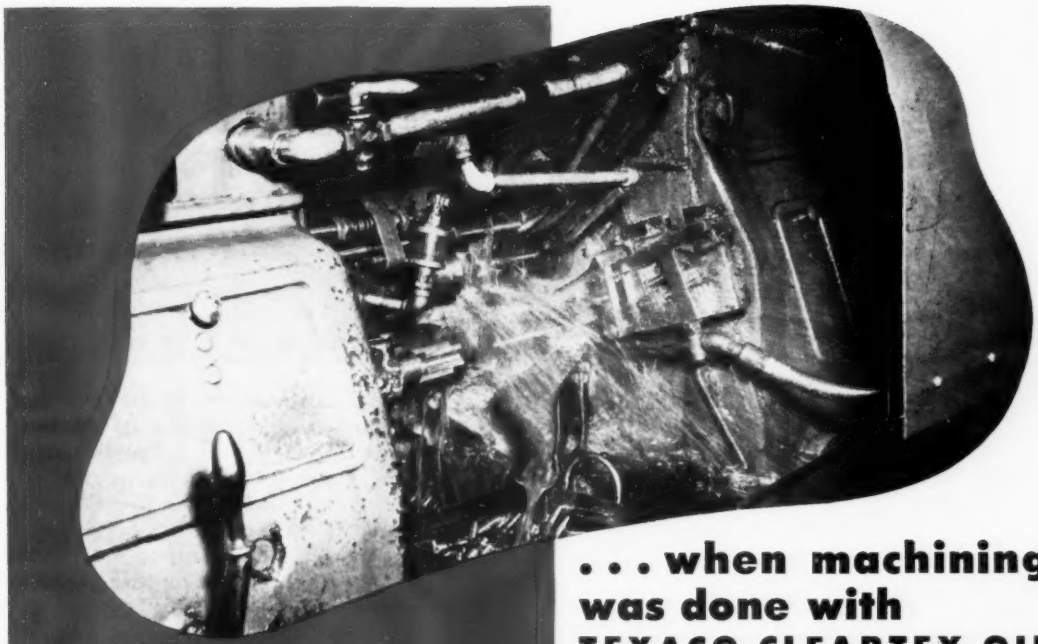


130% GREATER PRODUCTION between tool grinds...

. . . when machining was done with TEXACO CLEARTEX OIL

In this plant,* steel parts for pumps were being machined on Acme Gridley automatics. Two different competitive oils were being used — one as cutting fluid and the other as machine lubricant. Production lagged because of frequent tool changes, and contamination of coolant by machine oil necessitated frequent oil changes.

Then a Texaco Lubrication Engineer was asked what could be done to speed up production. He recommended using *Texaco Cleartex Oil B* as both coolant and machine lubricant. One oil thus replaced two; contamination problems and oil wastage were eliminated — and *production between tool grinds immediately jumped 130%!*

Machining stainless steel on the same set-up, use of *Texaco Cleartex Oil B* increased production between tool grinds 42%.

Let a Texaco Lubrication Engineer specializing in metal working help you gain increased production and lower unit costs in *your* plant. There is a complete line of Texaco Cutting, Grinding and Soluble Oils to help you do every machining job better, faster and at lower cost.

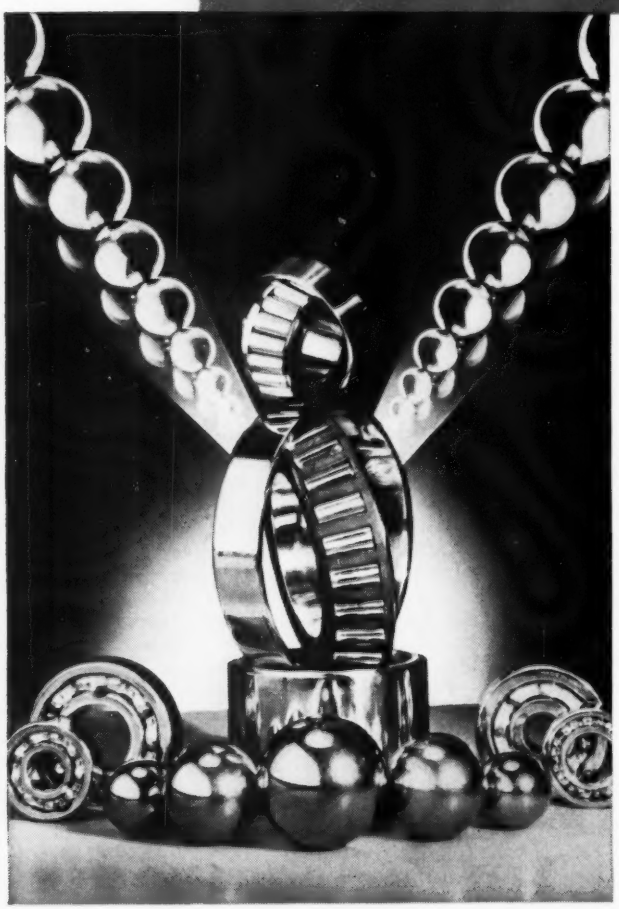
Just call the nearest of the more than 2,000 Texaco Distributing Plants in the 48 States, or write The Texas Company, 135 East 42nd Street, New York 17, N. Y. **Name on Request*

TEXACO CUTTING, GRINDING AND SOLUBLE OILS FOR FASTER MACHINING

Faithfully yours 50 *for Fifty Years*

LESS DOWNTIME, MORE PRODUCTION

for Hoover Ball and Bearing Company



As one of America's leading bearing manufacturers, Hoover Ball & Bearing Company, Ann Arbor, Michigan, is always searching for ways to step up production and improve quality. In the course of this never-ending program, Hoover called in a Texaco Lubrication Engineer for consultation.

The Texaco Lubrication Engineer studied thoroughly all the problems involved, then made recommendations which included changing from a competitive grinding oil to a 1-to-50 emulsion of *Texaco Soluble Oil D.* The change was made. Now production is up, costs are down because, with Texaco —

- *machines stay clean*
- *grinding finish has improved*
- *there is no rusting*
- *emulsion filters properly, does not separate, lasts far longer*

Here again is an example of how Texaco quality products plus the know-how of Texaco Lubrication Engineering Service enable all industry to do its machining better, faster, and at lower cost.

To enjoy these benefits in your plant . . . whatever you are making, wherever located . . . just call the nearest of the more than 2,000 Texaco Distributing Plants in the 48 States or write The Texas Company, 135 East 42nd St., New York 17, N. Y.

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